The behaviour of multi-bay, two-way reinforced concrete slabs in fire

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ABSTRACT: This paper describes numerical modelling of the fire behaviour of a multi-bay building having two-way reinforced concrete slabs supported by corner columns. The building consists of three bays by three bays and it is assumed that all bays of the building are subjected to fire. Two fires were used: one was the standard ISO834 fire having a 4 hour duration, while the second one was a parametric fire based on the ISO fire with the fire dying out after one hour and the temperatures decaying back to ambient after approximately another two hours. The effects of the fires in relation to the redistribution of bending moments and the development of tension field action are described.

1 INTRODUCTION

The design of reinforced concrete slabs for fire resistance is usually based on prescriptive generic ratings that specify the minimum slab thicknesses and the required concrete cover to the reinforcing steel. These generic ratings are generally conservative and have been based on standard fire tests using furnaces which are seldom representative of actual construction practices in that they do not account for the effects of axial restraint at the slab supports. The ratings of restrained floor systems are generally higher than those for unrestrained floor systems since tests have shown that the compressive restraint from the surrounding structure will improve the fire resistance of the floor system [Buchanan 2001].

Tensile membrane action has been known to structural engineers for 40 years. Park [1964] developed a theory to determine the load carrying capacity at large deflections by considering the tensile membrane action. Park et al. [2000] described how significant tensile membrane action in slabs can occur only if the movement of the edges of slabs is restrained when the slabs are at ambient temperatures. The tensile membrane action of slabs is not fully understood at elevated temperatures. However, based on the tests [Bailey et al., 2000a, 2000b; Bailey, 2001, Bailey, 2004], a design method for determining the ultimate load carrying capacity of two-way slabs has been developed by considering the effects of tensile membrane enhancement at elevated temperatures. The tensile membrane action in slabs is sensitive to the duration of fire exposure, the restraint of the edges of slabs, and the arrangement of reinforcing bars in slabs.

Compressive membrane action has been found in experimental fire tests of slabs exposed to fire [Selvaggio et al., 1963; Issen et al., 1970]. These tests have shown that the compressive membrane action can increase the fire resistance of reinforced concrete. Several researchers [Anderberg et al., 1982; Harmathy, 1993; Lim et al, 2004] found that the compressive membrane action is sensitive not only to the duration of fire exposure, the location of the restraint on the edges of slabs and the arrangement of reinforcing bars in slabs, but also to the ratio of the span to the thickness of slabs.

Redistribution of bending moments can occur when plastic hinges develop in slabs. The redistribution of bending moments can give significant advantages in the fire design of continuous structural members [Buchanan, 2001]. When the redistribution of bending moments occurs, the cold top reinforcing bars have to resist the larger applied moments, while the hot bottom reinforcing bars resist smaller applied moments due to the reduced yield strength of the bars at elevated temperatures. 3-D analyses for reinforced concrete floor systems in fire exposure can be performed using special purpose computer programs, such as SAFIR [Franssen et al 2002]. The design of reinforced concrete floor systems exposed to fire is more complicated and difficult than the design of structural members because lateral deformations and resulting P-Δ effects must be considered in the design of the floor systems.

This paper investigates the fire performance of two-way reinforced concrete slabs. The behaviour of a three by three bay slab subjected to fire over its whole area is compared with that of the same slab in an arrangement where the ISO fire is used with the fire dying out after one hour and the temperatures decaying back to ambient after approximately another two hours.

2 STRUCTURAL DETAILS/DESIGN

The structure analysed is a two storey building with the floors and roof being reinforced concrete flat slabs supported on columns. The storey height of each level is 3.6 m. The centre-to-centre spans of the bays are 6 m in both directions. The building comprises nine 6 m square panels arranged in a three by three layout and the thickness of the slab is 0.2 m. The cross-section of the columns is 0.5 m square. The four outer edges of the floor slabs are supported by edge beams 0.25 m wide by 0.5 m deep which connects the edge and corner columns. Because of the symmetry of the structures, only a quarter of the structure is modelled. The fire is assumed to occur on the ground floor (level one) and therefore affect the first floor slabs (level two).

The flat slab was designed according to the ***direct design method*** of Section 13.6 in *ACI 318R-89* (ACI, 1992). The X-direction reinforcing bars were placed on the top of the Y-direction reinforcing bars of the slab. The reinforcement of all the columns and beams is the same throughout. Details are given in Wang (2004)

The concrete was assumed to be made using silaceous aggregate having a compressive strength of 30 Mpa and zero tensile strength. The reinforcing steel was assumed to have a yield strength of 430 Mpa. The uniformly distributed fire load on the flat slab was calculated to be 6.9 kN/m^2.

3 ANALYTICAL MODELLING

3.1 *Fire exposure*

The bottom of the concrete slab was exposed to either a fire with a growth rate that followed the ISO 834 [ISO 1975] fire, or to a parametric fire based on the ISO fire where the fire died out after one hour with the temperatures decaying back to ambient as shown in Fig. 1. The temperatures in the slab varied only through the thickness. The columns in the 3 x 3 bay structure were not exposed to the fire and remained at the ambient temperature.

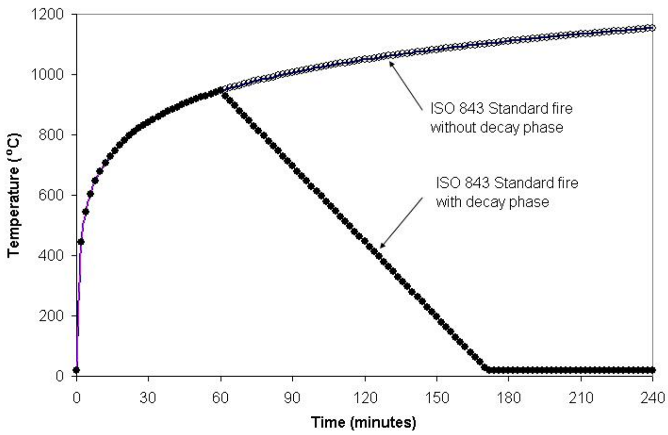

Figure 1 ISO 834 Standard fire curves with or without a decay phase.

3.2 *Structural analysis*

Because of symmetry, only one quarter of each structure needed to be modelled. The columns were taken as fully fixed at the base, and restrained against all but vertical movement at the top. A segment of columns above or below the first floor level is discretized to nine beam elements. The beam members are discretized to a number of 0.3m long beam elements. The concrete slab is modelled as 0.3m square shell elements.

4 RESULTS FOR THE ISO FIRE EXPOSURE

The top view of a quarter of the nine-bay flat slab is shown in Figure 2. For a convenient description of the behaviour of the slab, 16 points, 5 strips and 5 sections are defined. Points-B2, -B4, -D2, and -D4 are at the centroid of the columns, while Point-A1 is the central point of the nine-bay slab. Point-A1 is also the absolute zero coordinate point. The strips

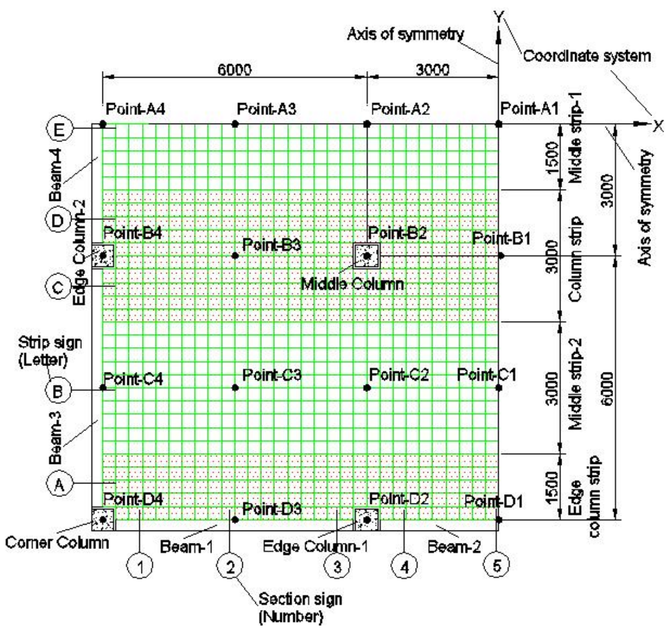

Figure 2 Reference diagram for the nine-bay flat slab (one quarter of the slab shown)

along the X-direction are indicated by letters, whilst the sections along the Y-direction are indicated by numbers. Some terms which will be used in further discussions are shown in Figure 2 as well (for example: Edge Column-1, Beam-1).

4.1 *Displacements*

4.1.1 *Vertical deflections*

Figure 3a shows the vertical deflections of the slab at Points-A1, -B1, -C1, and -D1. The deflection at Point-D1, which is a common point between the beam element and the shell element, was always very small because of the large flexural stiffness of the edge beams that were partially exposed to the fire. For the first 30 minutes, the deflections of the other three points were almost the same. After this, the deflection of Point-C1 in Middle-strip-2 exceeded that at Point-B1 in the Column strip because of the redistribution of the bending moments in the slab. The largest deflection of the slab was at Point-

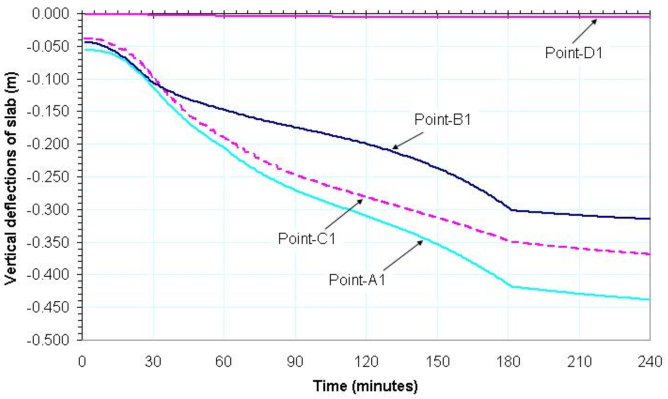

Figure 3a Vertical deflections of the slab at Point-A1, -B1, -C1, and -D1

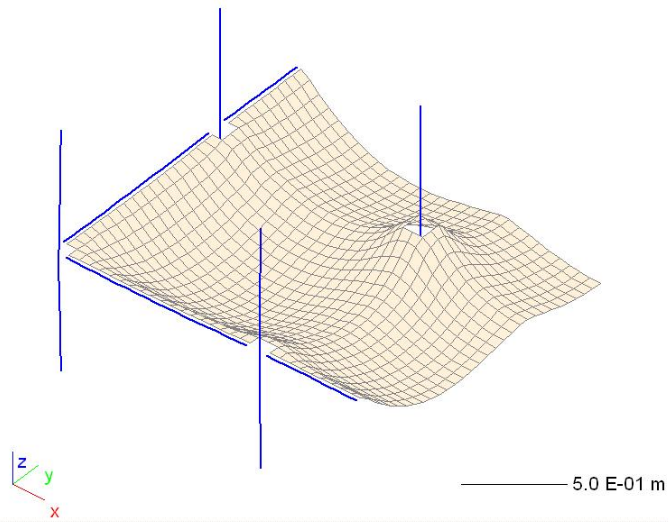

Figure 3b Vertical deflected shape of the slab at 180 minutes (scale factor: 5)

A1, the central point of the nine-bay flat slab. The change in the deflection curves at 180 minutes occurred when part of the slab became a catenary.

Figure 3b shows the deflected shape of the slab after 180 minutes. The graph shows that the vertical deflections of the slab between the columns were less than in the central parts of the slab. The slab deformed as a catenary hanging on the columns, the column strips, and the beams. Collapse did not occur since the top reinforcing bars in the slab were anchored into the edge beams and columns. If the top reinforcing bars of the slab fail to anchor into the columns and beams, the slab will collapse.

4.1.2 *Horizontal displacements*

Figure 4a shows the X-direction displacements at Points-B2, -B4, -D2, and -D4, i.e. the centroids of the columns. The figure shows that the corner column and two edge columns moved outwards from the centre of the flat slab (the negative value of horizontal displacements), whilst the middle column moved towards the centre of the flat slab (positive value of horizontal displacements). The horizontal displacements of the columns were mainly affected by the thermal expansion of the slab and the edge beams in the first stage of the fire. As the vertical displacements of the slab became larger, P-Δ actions in the slab developed quickly due to the tensile membrane forces and the thermal bowing action. In the absence of edge beams, the tensile membrane

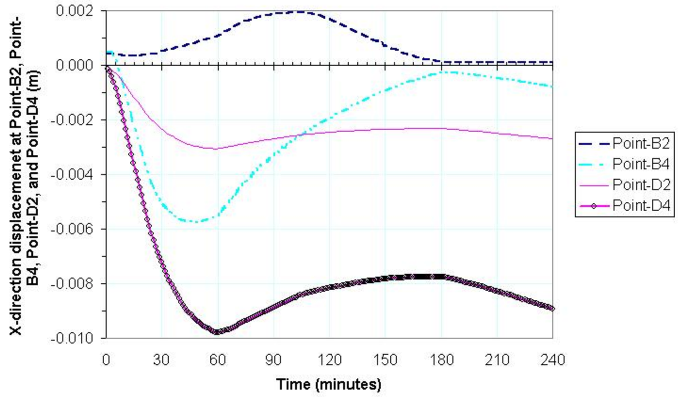

Figure 4a X-direction displacements at Point-B2, Point-B4, Point-D2, and Point-D4

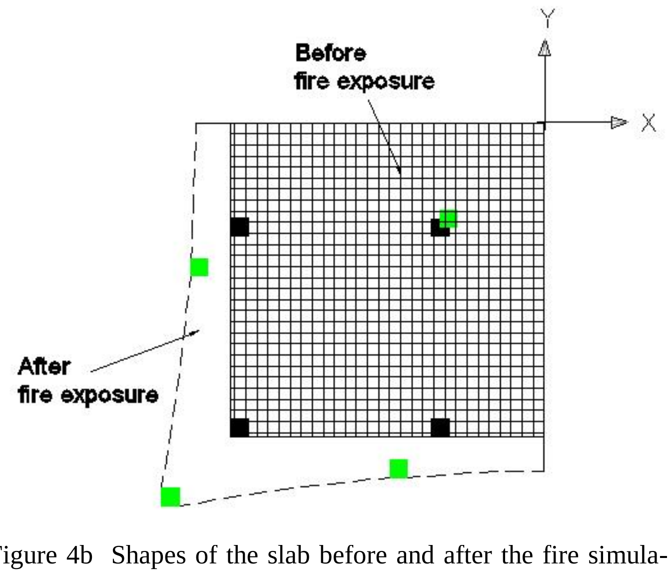

Figure 4b Shapes of the slab before and after the fire simulation

forces (especially in Column strip) would tend to pull the columns towards the central point of the slab (Point-A1). The outwards movement of the corner column throughout the simulation of the fire indicates that the horizontal movements of the corner column were dominated by the thermal expansion and horizontal thermal bowing of the edge beams. The vertical thermal bowing of the edge beams was small due to the fire exposure mainly being on the inside vertical surface of the beams. At the end of the simulation, the shape of the slab is shown in Figure 4b. The horizontal movements of the edges of the slab had a tendency to enhance the development of the tensile membrane forces in the slab and reduce the vertical deflections of the slab.

4.2 *Bending moments*

Because the slab is symmetrical about both axes, only X-direction bending moments are presented. An analysis of the bending moments in the slab shows that the redistribution of bending moments is significantly affected by the arrangement and magnitude of the top reinforcing bars in the slab. The redistribution of bending moments in the slab is one of the main factors affecting the fire endurance and capacity of preventing the collapse of the slab.

4.2.1 *Development of X-direction bending moments*

Figure 7a shows that the average bending moments in the strips along Section-1 were positive throughout the simulation of the slab in the fire. The bending moments in the Edge column strip, Middle strips-1 and -2 have similar trends to the curve in Column strip, but the magnitude of the bending moments was smaller than in the Column strip. In comparison, Figure 7b shows that the average bending moment in Column strip along Section-5.

The main trend of the redistribution of bending moments in the slab is from the negative bending moments (the tensile forces in the bottom reinforcing bars) to the positive bending moments (the tensile forces in the top reinforcing bars) because the temperatures of the reinforcing bars in the bottom of the slab rise more quickly than in the top of the slab. The negative flexural capacity of the slab declines when the temperatures of the bottom reinforcing bars exceed 300^{o}C because the yield strength of the hot-rolled steel starts to decrease at 300^{o}C.

4.3 *Membrane forces*

The average membrane forces along Section-1 and Section-5 in the Edge column strip, Column strip, and Middle strips-1 and -2 are shown in Figures 8a and b and can be seen to be similar. The phenomenon of the tensile membrane force lag is present in Middle strips-1 and -2 because of the effect of the

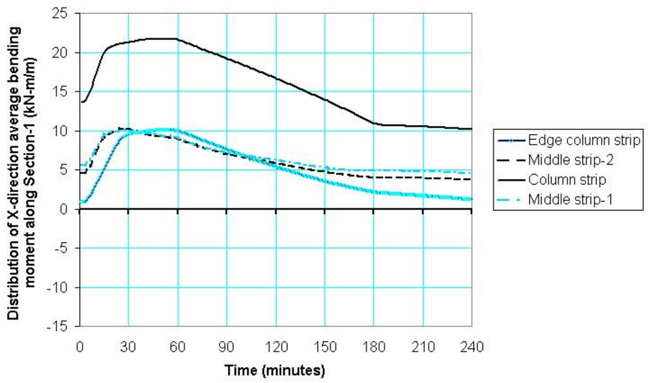

Figure 7a X-direction average bending moments in the strips along Section-1

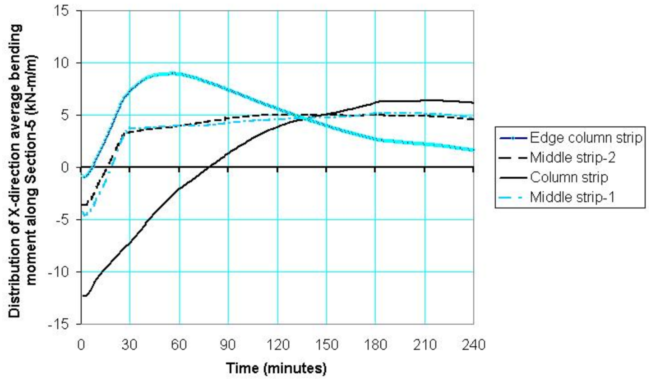

Figure 7b X-direction average bending moments in the strips along Section-5

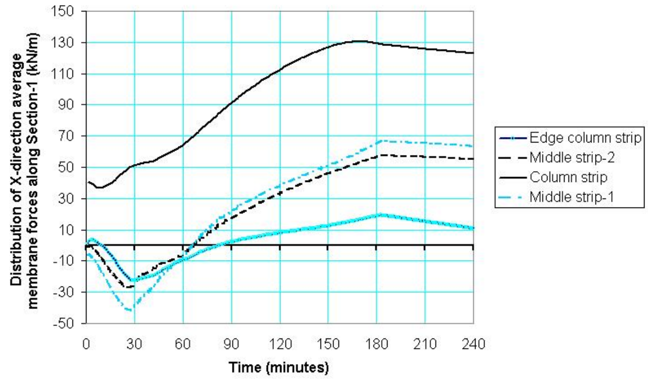

Figure 8a X-direction membrane forces in the strips along Section-1

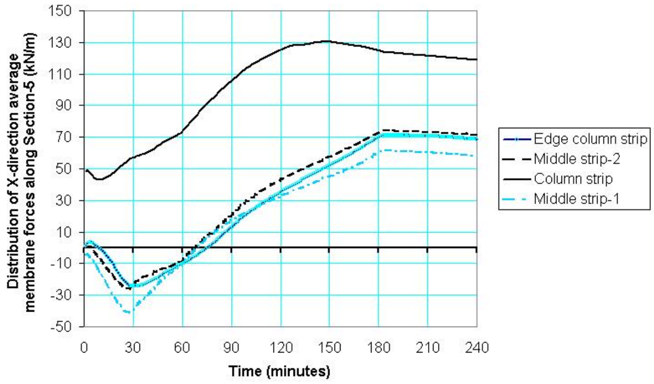

Figure 8b X-direction membrane forces in the strips along Section-5

restraint of the columns and edge beams on the slab. Therefore, the reinforcing bars, especially the top reinforcing bars, arranged continuously in the column strips can enhance the capacity of preventing the collapse of the slab.

5 RESULTS FOR FIRE EXPOSURE WITH A DECAY PHASE

5.1 *Displacements*

5.1.1 *Vertical deflections*

Figure 9 shows the vertical deflections of the same points shown in Figure 3a. It can be seen that in the case of a parametric fire, the deflections remain reasonably constant during the decay phase of the fire and after. The deflected shape of the slab after the fire temperature has decayed to ambient is similar to that in the ISO fire (Figure 3b).

5.1.2 *Horizontal displacements*

The deflections at Points-B2, -B4, -D2, and –D4 are shown in Figure 10. Once the fire goes out at 60 minutes, the deflections reduce considerably in the case of the Edge and Corner columns. For the Edge column at Point-B4, the tensions in the column strip of the slab cause movement towards the centerline of the slabs.

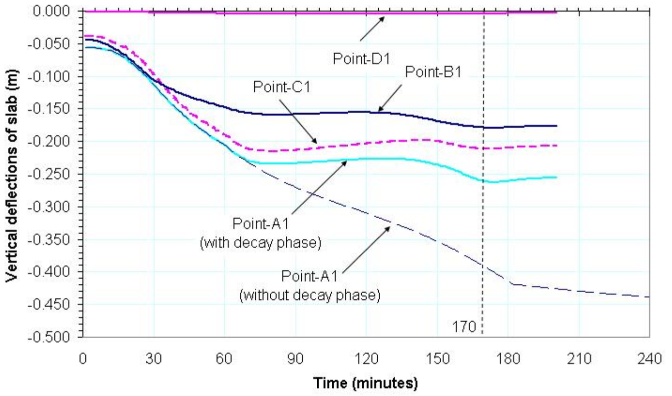

Figure 9 Vertical deflections of the slab at Points-A1, -B1, -C1, and –D1

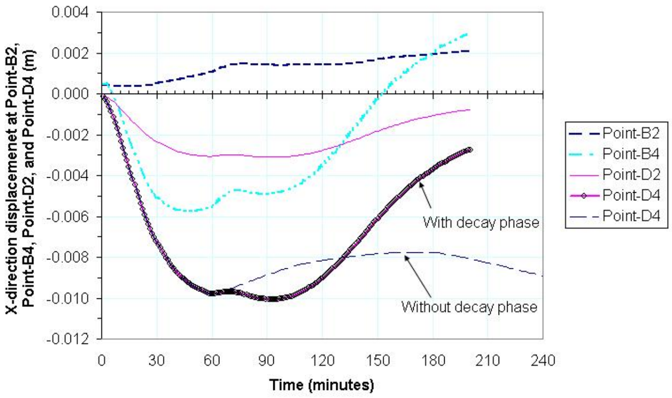

Figure 10 X-direction displacements at Points-B2, -B4, -D2, and -D4

5.2 *Bending moments*

5.2.1 *Development of X-direction bending moments*

The average bending moments in the strips along Sections-1 and -5 are shown in Figure 11a and b. By comparison with Figures 7a and b, it can be seen that once the fire goes out, the bending moments in the strips change appreciably. Along Section-1, the moments change from positive to negative, while along Section-5, the moments change in a similar manner.

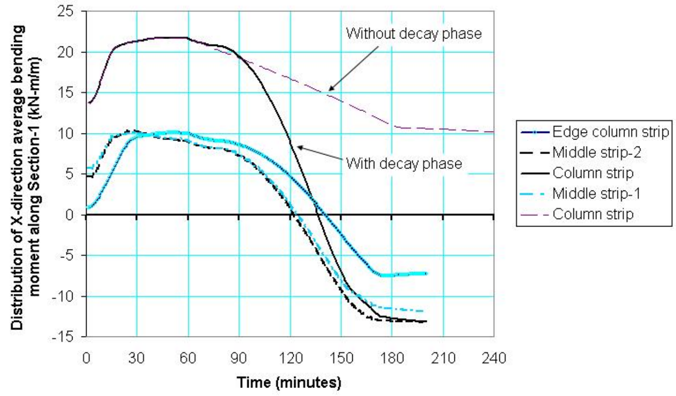

Figure 11a X-direction average bending moments in the strips along Section-1

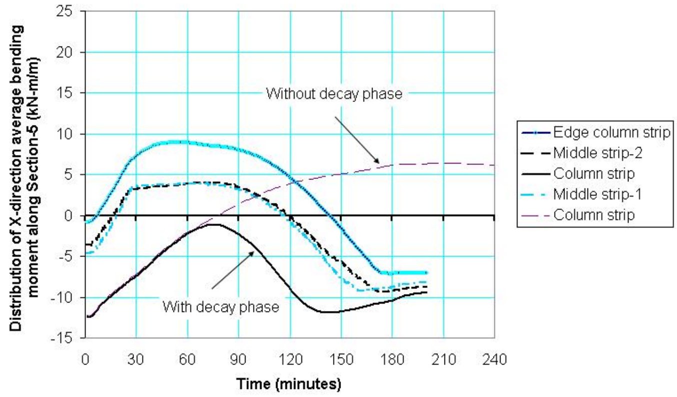

Figure 11b X-direction average bending moments in the strips along Section-5

5.3 *Membrane forces*

The X-direction membrane forces are shown in Figure 12a and b and can be compared with those from the ISO fire in Figure 8a and b. It can be seen that for the parametric fire, the membrane forces are similar along both sections and continue to increase even after the fire temperature has decayed back to ambient.

6 DISCUSSION

In the case of the ISO fire, the bottom of the concrete and the bottom reinforcing steel heat up well before the top reinforcing and the top of the concrete. Once the steel temperature exceeds 300°C, the yield strength of the steel decreases with increasing temperature. This means that the positive bending strength of the concrete section will diminish with increasing time and temperature as will its membrane strength.

For the case of a shorter fire, once the fire goes out and the decay phase starts, the bottom of the concrete will start to cool. The yield strength of the bottom reinforcing will increase and it will also contract. The overall effect causes compressive membrane stresses to develop in the top of the slab.

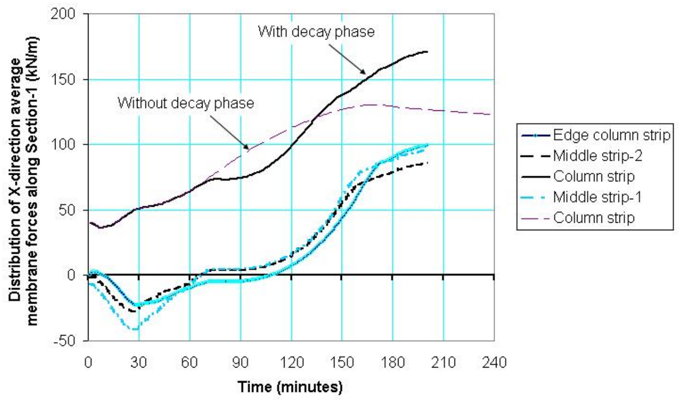

Figure 12a X-direction average membrane forces in the strips along Section-1

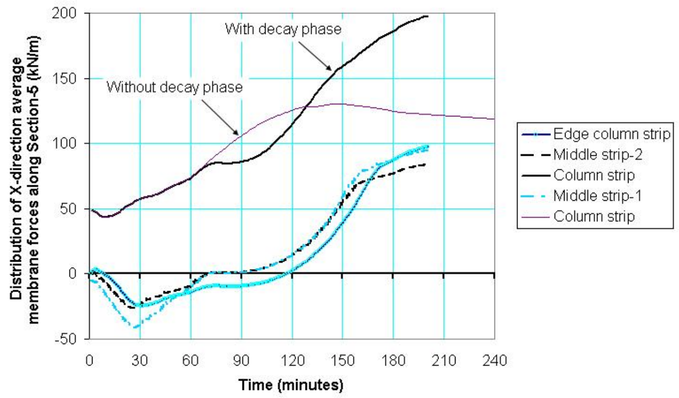

Figure 12b X-direction average membrane forces in the strips along Section-5

Since the edge beams are heated on one side only, they will be subject to thermal bowing in one direction throughout the duration of the fire. However, in the shorter fire exposure, the thermal bowing changes direction during the decay phase. The behaviour in the shorter fire differs from that in the continuous ISO fire on account of the different interactions that take place between the expansion, or contraction, of the slabs and the bowing of the edge beams.

7 CONCLUSION

The analysis of the nine-bay flat slab exposed to fire with or without a decay phase has found that:

- In the ISO fire, the bending moment is redistributed as the bottom steel heats up, and the slab loses strength after the bottom steel temperature exceeds 300^{o}C. The bending moments in the slab reach a peak when the top steel reaches 300^{o}C and the slab loses strength as the top bars heat up further.
- Where there is a decay phase, the average bending moments in the slab change from positive to negative as the slab cools down.
- For the fire with a decay phase, the membrane forces become tensile and keep increasing as the fire goes out whereas for the continuous fire the forces are limited by the loss of strength in the reinforcing bars as they heat up.
- The thermal conditions of the edge beams significantly affect the vertical and horizontal displacements of the slab.

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